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Abstract

Use of the National Ignition Facility to also output frequency-doubled (.53μm) laser light would allow significantly more energy to be delivered to targets as well as significantly greater bandwidth for beam smoothing This green light option could provide access to new ICF target designs and a wider range of plasma conditions for other applications. The wavelength scaling of the interaction physics is a key issue in assessing this green light option. Wavelength scaling theory based on the collisionless plasma approximation is explored, and some limitations associated with plasma collisionality are examined. Important features of the wavelength scaling are tested using the current data base, which is growing. It appears that, with modest restrictions, .53μm light couples with targets as well as .35μm light does. A more quantitative understanding of the beneficial effects of SSD on the interaction physics is needed for both .53μm and .35μm light.

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Introduction

In its standard mode of operation, the National Ignition Facility (NIF) will output frequency-tripled Nd laser light (3ω or .35μm light). However, NIF is also capable of outputting frequency-doubled (.53μm) laser light. This so-called .53μm light option[1] could significantly enhance NIF's capabilities. Due to higher optical damage thresholds for frequency-doubled light and higher conversion frequency into 2ω light, the laser energy on target could be very significantly increased (perhaps by a factor of two). Furthermore significantly greater bandwidth can be achieved with 2ω operation, allowing for enhanced laser beam smoothing. Lastly, a 2ω driver could allow efficient diode-pumped solid-state laser designs to be used for an inertial fusion power plant.

The .53μm laser option would significantly broaden the options for ICF target design. The greater laser energy at 2ω would enable design of larger hohlraum targets with a capsule absorbed energy >1MJ. According to recent designs[2], these larger targets could be irradiated with a peak laser intensity $< 3x10^{14}$ W/cm^2 and have density profiles (normalized to the critical density) in the irradiated plasma quite similar to those in hohlraums irradiated with 3ω light. More laser energy on target and more beam smoothing would also benefit other experiments on high energy density physics.

Whether these many potential benefits are achievable depends on the wavelength scaling of the coupling physics. We here examine a wavelength scaling model based on the collisionless plasma approximation. Let's first discuss the model and some restrictions associated with collisionality. Then we will test and illustrate this model by applying it to recent data on stimulated Raman scattering of .53μm and .35μm light.

Wavelength scaling model

It is straight-forward to obtain a wavelength scaling model. Consider an intense light wave with electric and magnetic fields E and B, frequency ω_0, and wavelength λ_0 propagating into a collisionless plasma with electron density n, electron temperature T_e, ion temperature T_i, and ion charge state Z. In the collisionless plasma limit (number of electrons per Debye sphere infinite), the interaction physics is completely described by the Vlasov equation coupled with Maxwell's equations. The scaling variables are obtained by simply defining dimensionless variables for these equations.

Let's take a more physical approach and imagine that one is about to carry out a PIC simulation of the plasma evolution. If a sufficient number of particles are used, such a simulation is fully equivalent to a solution of the Vlasov equation[3]. To define the simulation, it suffices to specify the following variables:

$$\frac{eE}{m\omega_0 c} = (\frac{I\lambda_\mu^2}{1.35x10^{18}})^{.5}, \qquad \frac{\omega_{pe}}{\omega_0} = (\frac{n\lambda_\mu^2}{1.1x10^{21}})^{.5}, \qquad (1)$$

$$\frac{v_e}{c} = \left(\frac{T_e}{511}\right)^{.5}, \quad \frac{L_\mu}{\lambda_\mu}, \frac{T_i}{T_e}, \text{and Z.} \qquad (2)$$

Here I is the laser intensity in W/cm^2, ω_o the laser frequency, and λ_μ is the laser wavelength in microns. T_e (T_i) is the electron (ion) temperature in keV, and L_μ is the plasma length in microns along the direction in which the laser propagates. Note that for simplicity we have taken a plane wave incident onto a plasma slab with a uniform density and temperature. Of course, in general the laser spot size, the transverse plasma size and the gradients lengths-all normalized to the laser light wavelength- are variables., as well as various laser properties such as the bandwidth normalized by the laser light frequency.

It is clear that the nonlinear solution obtained in the simulation (which can be as elaborate as you can imagine) applies not just to a plasma irradiated with laser light of some specific wavelength but for laser light of any wavelength as long as the scaling variables are respected. The scaling model is then very powerful. The scaling applies no matter how complex the mix of nonlinear processes. The scaling model is potentially very useful. We can use the large data base on the coupling physics obtained with .35μm laser light to provide estimates for the analogous results to be expected with .53μm laser light.

Of course, the scaling model requires validation. For example, it strictly applies to collisionless plasmas, which is an ideal limit. The model is expected to be most useful well above collisional instability thresholds and when the results are not extremely sensitive to minor variations in parameters, such as the temperatures or the details of the beam smoothing.

Some effects of collisionality

In practice, plasma collisionality does play some role; for example, in setting the background plasma temperature via inverse bremsstrahlung absorption. As a simple model, let's consider laser light propagating through an underdense plasma with uniform density n. length L, and ion charge state Z. The fractional absorption (assumed small) is

$$f_{abs} = \left(\frac{n}{n_{cr}}\right)^2 \frac{v_{ei}L}{c}, \qquad (3)$$

where ν_{ei} is an electron-ion collision frequency and c the velocity of light. The electron temperature is estimated via a free-streaming model with a flux limit of .1, giving

$$f_{abs}I = .1nT_e v_e, \qquad (4)$$

where v_e is the electron thermal velocity. The temperature then becomes

$$T_e = \left(\frac{22ZL}{\lambda_\mu^2} \frac{I\lambda_\mu^2}{2x10^{13}} \frac{n}{n_{cr}} \right)^{\frac{1}{3}}. \qquad (5)$$

Consider an example motivated by a hohlraum filled with low Z gas and irradiated with .35μm light. For Z=2, L=3mm,n/n_{cr}=.1, and I=2x10^{15} W/cm^2, T_e~5keV. The corresponding scaled irradiation with .53μm light (L~5mm, I~10^{15} W/cm^2, n/n_{cr}=.1) would give T_e~4.4 keV, not exactly the same but close.

Collisionality also introduces a threshold intensity for laser plasma instabilities, a beneficial effect. However, these thresholds are quite low in high temperature, low Z plasmas and rather low even in hot, high Z plasmas. As an example, consider the threshold intensity (I_T) for stimulated Raman scattering near .25 n_{cr} due to electron-ion collisions. If we use equation (5) to estimate T_e,,

$$I_T \sim \frac{5x10^{11}}{\lambda_\mu^2} \sqrt{\frac{Z}{L}} \frac{W}{cm^2}. \qquad (6)$$

To illustrate the numbers, take λ_μ=.35 and L=.3cm. Then I_T~2x10^{13} W/cm^2 for Z=3.5 and I_T~7x10^{13} W/cm^2 for Z=50.

Thermal filamentation is another effect due to collisionality. Indeed this process can be efficient in high Z plasmas, especially when nonlocal heat transport is taken into account. For example, consider a plasma with density .1 n_{cr}, Z=50, and T_e=4 keV irradiated with .35μm light with an intensity of 10^{15}W/cm^2. Then the nonlocal theory of Epperlein[4] predicts a spatial gain rate of about .26/μm for a most unstable transverse wavelength of about 7.9μm. Thermal filamentation could actually be a beneficial effect, since it enhances the incoherence of the laser light and drives up long wavelength density fluctuations.

Wavelength scaling: tests and implications

The wavelength scaling model is quite supportive of the .53μm laser option for NIF. Green light is predicted to couple with targets as well as blue light does, provided some modest restrictions are respected in the target designs. For gas-filled holhraums, the profiles of density times the square of the wavelength should be the same, the laser intensity times the square of the wavelength the same, and so forth. As emphasized by Suter *et. al.*, the larger energy available with 2ω operation allows such targets to be designed; i.e., larger hohlraums with lower radiation temperature filled with plasma at a lower density and irradiated with light at a lower intensity.

Recent experiments seem quite consistent with the predictions of the wavelength scaling model. To be specific, let's consider the stimulated Raman scattering measured in experiments[5-9] in which long scalength plasmas were irradiated with .35μm and .53μm light. Table 1 shows a variety of results with C_5H_{12} targets with a density of about .1 n_{cr}.

With one exception $I\lambda_{\mu}^{2} \sim 2x10^{14} W-\mu^{2}/cm^{2}$. T_e is about (2±1) keV, and L/λ_0 is typically ~(4-6)x10^3. The targets include foils, gas bags, and gas-filled hohlraums. Note that despite modest variations in the scaling parameters, the SRS reflectivities are quite similar: typically 15-30%. In these experiments, neither SSD nor polarization smoothing was used. Table 2 shows analogous results for higher Z targets with similar conditions. Note that the SRS reflectivities are again quite similar (<1%).

λ_μ	n/n_{cr}	$I\lambda_{\mu}^{2}$	L/λ	T_e (keV)	Target	r_{SRS} (%)	Expt.
.35	.1	$2x10^{14}$	$6x10^3$	3	C_5H_{12}	20	Nova foils[5]
.35	.1	$2x10^{14}$	$6x10^3$	3	C_5H_{12}	30	Nova hohlrm[6]
.35	.1	$2x10^{14}$	$6x10^3$	3	C_5H_{12}	12	Nova gas bag[7]
.53	.1	$2x10^{14}$	$2x10^3$	1	C_5H_{12}	15	Helen gas bag[8]
.53	.1	$2x10^{14}$	$4x10^3$	2	C_5H_{12}	15	Omega gas bag[9]
.35	.1	$8x10^{13}$	$4x10^3$	2	C_5H_{12}	20	Omega gas bag[9]

Table 1: the SRS reflectivity measured in a variety of experiments in which long scalelength low Z plasmas with density near .1 n_{cr} were irradiated with .35μm and .53μm laser light. The entries for n, I, T_e, and r_{SRS} are approximate.

λ_μ	n/n_{cr}	$I\lambda_{\mu}^{2}$	L/λ	T_e (keV)	Target	r_{SRS}(%)	Expt.
.35	.1	$2x10^{14}$	$6x10^3$	3	CO_2/CF_4	.2	Nova gas bag[10]
.35	.1	$8x10^{13}$	$4x10^3$	3	Xe	.1	Omega gas bag[9]
.53	.1	$2x10^{14}$	$4x10^3$	3	Kr	.5	Omega gas bag[9]
.53	.1	$2x10^{14}$	$2x10^3$	2	Kr	<1	Helen gas bag[8]

Table 2: the SRS reflectivity measured in a variety of experiments in which long scalelength higher Z plasmas were irradiated with .53μm and .35 μm laser light. The entries for n, L, I, and r_{SRS} are approximate.

Important dependencies of the SRS reflectivities on intensity and plasma density are also in reasonable accord with the wavelength scaling model. Figure1a shows the SRS reflectivity versus intensity measured in experiments in which C_5H_{12} gas bags with density about .1 n_{cr}, T_e~2 keV, and L/λ_0~4x10^3 were irradiated with .53μm light. For comparison, figure 1b shows the SRS reflectivity from experiments in which C_5H_{12} gas-filled holhraums with density about .1 n_{cr}, T_e~3keV, and L/λ_0~6x10^3 were irradiated with .35μm light. In both cases the reflectivity saturates with intensity above

$I\lambda_\mu^2 \sim 10^{14} W - \mu^2 / cm^2$. Figure 2 shows the SRS reflectivity as a function of plasma density at a given intensity ($I\lambda_\mu^2 \sim 2x10^{14} W - \mu^2 / cm^2$) in these experiments with .53μm and .35μm light. In each case, there is a similar decrease with density above about .1 n_{cr}.

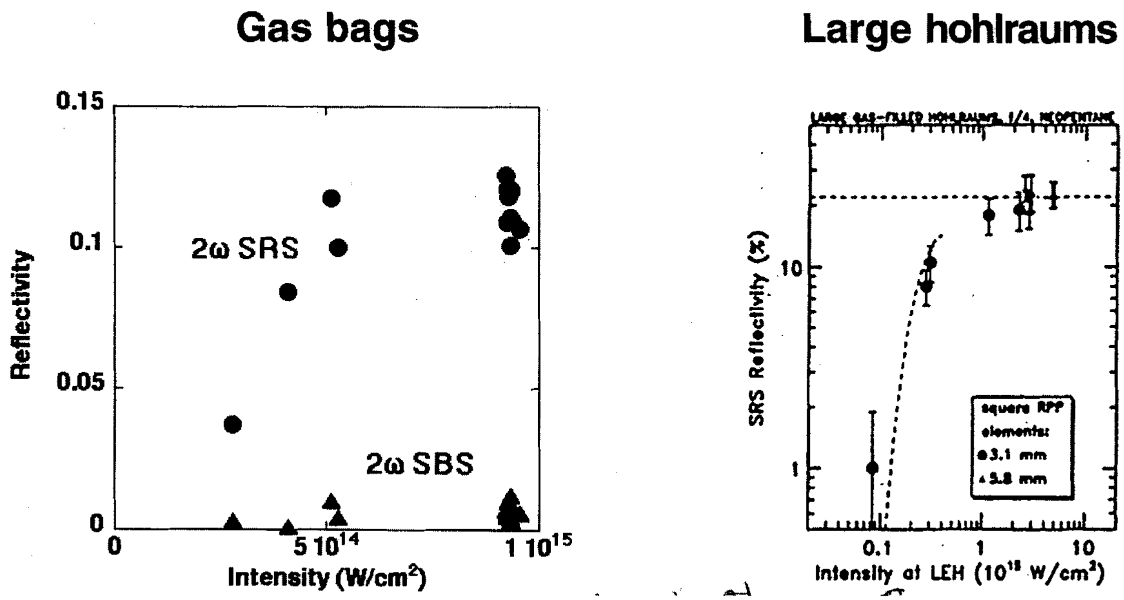

Figure 1: SRS reflectivity versus intensity measured in experiments a) in which gas bags with density ~.1 n_{cr} were irradiated with .53μm light[9] and b) in which gas-filled hohlraums with density ~.1 n_{cr} were irradiated with .35μm light[6].

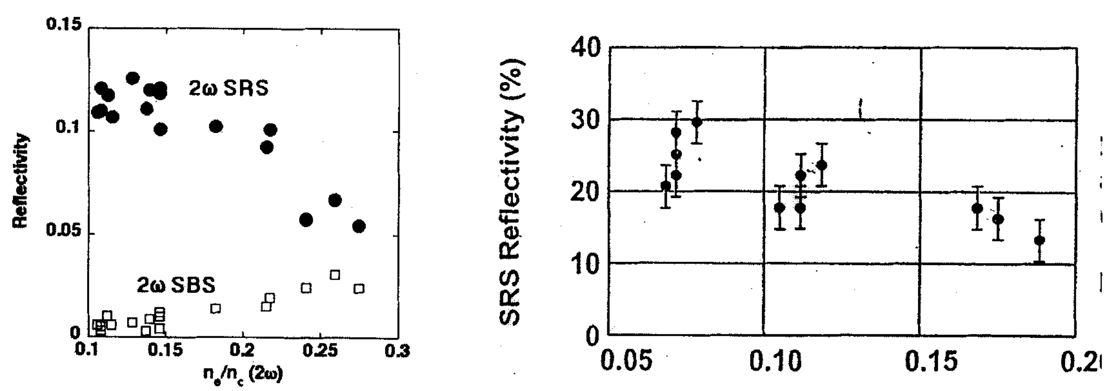

Figure 2:SRS reflectivity versus density measured in experiments in which a) gas bags were irradiated with .53μm light[9] and b) gas-filled hohlraums were irradiated with .35μm light[6].

Summary and discussion

The use of NIF to also output .53μm light is a very attractive option. The significantly greater energy and enhanced beam smoothing available with 2ω light enables a broader range of target designs both for ignition and for other studies of high energy density physics. According to a wavelength scaling model, .53μm light will couple with long scalelength targets as well as .35μm light does, provided some modest constraints are observed. Some recent experiments on SRS reflectivity of .53μm and .35μm light are in reasonable agreement with these scalings.

These promising results should be further tested in NIF early light (NEL) experiments. In future ignition experiments, the plasma temperature will be about 5-6 keV and the plasma size will be ~4-5 mm, which is greater than in current experiments. We note that a better understanding is needed for some important trends in the data base, such as the strong reduction of SRS in higher Z plasmas. Likewise, there is variability in the data base which is not well understood. For example, in some experiments with low density plasma (~.05 n_{cr}), the SRS reflectivity is significantly lower that that found in other experiments with nominally the same conditions. Lastly, we need to further test and understand the beneficial effects of SSD, particularly on stimulated Raman scattering.

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